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COST CONSIDERATIONS OF TRANSITION TOWARD A DISAGGREGATED SATELLITE ARCHITECTURE

by

Eric J. Felt, Lt Col, USAF

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Advisor: Col Don E. Hill, USAF

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Biography

Lieutenant Colonel Eric Felt is a US Air Force acquisition officer assigned to the Air War College, Air University, Maxwell Air Force Base, Alabama. He received his commission in 1991 from Air Force Reserve Officer Training Corps upon graduation from Duke University with a Bachelor of Science degree in Electrical Engineering, Computer Science, and History. He entered active duty in 1996 after completing Master of Science and Doctor of Philosophy degrees in Electrical Engineering and Computer Sciences at the University of California, Berkeley. He is a Flight Test Engineer graduate of the US Air Force Test Pilot School and has served as a developmental engineer and program manager in lab, test, program office, and staff assignments. His focus area for the past 10 years has been space acquisition and he is a graduated materiel leader.

Abstract

The US is disaggregating space architectures by splitting missions currently combined on large satellites into mission-specific smaller satellites. Disaggregation offers five potential key advantages: resiliency, technology refresh, industrial base, adaptability, and cost. Experts essentially concur on the first four advantages, but disagree about cost.

The reason for disagreement on whether disaggregation will save money is that space system cost modeling depends heavily on the assumptions underlying the models. Based on the assumptions currently used today, disaggregation is likely to cost more than continuing the status quo; modeling the costs to disaggregate a hypothetical communications satellite into four smaller satellites illustrates this finding.

The key to lowering the cost of disaggregation is to examine the major underlying assumptions that are driving cost conclusions. Cost advantages will emerge from disaggregated architectures when the US significantly reduces launch costs, significantly increases resiliency requirements, and/or values architecture flexibility more highly.

All three of these factors advantageous to disaggregated architectures are trending favorably and the US could accelerate them to enable cost-effective disaggregation. The US should switch to competitively procured US commercial launch capabilities, backed up by foreign capabilities when needed. In addition, the US national security space enterprise should incorporate resiliency requirements into space architectures and value architecture flexibility more highly. Finally, the US must recognize that the transition to disaggregated architectures will be challenging, politically more than technically. US space leaders should pay attention to disaggregation implementation details such as budget phasing, formal requirements and policies, and countering inertia and other barriers to change.

Introduction

If you dislike change, you're going to dislike irrelevance even more.
General Eric Shinseki[1]

The US national security space enterprise is entering a period of change. The change is both unwanted and inevitable. The change is unwanted because the enterprise has mostly recovered from a tumultuous period of failed and canceled programs that germinated with acquisition reform in the 1990s; the enterprise would like to continue with architectures that are now working.[2] The change is inevitable, though, because the nation's long-term fiscal situation and priorities are leading to declining budgets. Current space architectures are unsustainable, even with flat budgets, and cannot gracefully absorb budget cuts.[3]

Though unwanted and inevitable, the coming change is good and there is little reason to fear or fight it. The transition through the period of change is also imminently manageable. In addition to recognizing and emphasizing the urgency for change, the commanders of Air Force Space Command (AFSPC) and the Space and Missile Systems Center (SMC) have explained the desired end state: **affordable and resilient architectures**. To reach this end state, the US must disaggregate, with capabilities currently residing on a few large satellites migrated to a greater number of smaller satellites.[4]

There are five potential key advantages of disaggregated architectures: resiliency, technology refresh, industrial base, adaptability, and cost. Resiliency refers to an architecture's ability to continue to provide needed capabilities in spite of hostile action or adverse conditions.[5] Clearly, if a constellation consists of only one large satellite and that satellite is lost, the effect is much greater than if a constellation consists of 20 small satellites and one is lost. Technology refresh opportunities and industrial base advantages accrue from manufacturing more satellites

on shorter production timelines. Large and complex satellites are less conducive to technology insertion because the consequences of potentially inducing a mission failure are so high. The high cost of complex satellites leads to low production rates that are not cost-effective and allow workforce skills to atrophy. Disaggregation increases adaptability because 1) programs can more easily modify smaller satellites to incorporate new capabilities for emerging threats, and 2) programs can more gracefully adjust the architecture itself to accommodate budget changes. These first four potential key advantages of disaggregation are reasonably well recognized and understood.[6]

Space experts disagree about the fifth potential advantage of disaggregated architectures: cost. The answer to whether disaggregated architectures are less expensive depends on the details of each mission area and, importantly, the assumptions used for the analysis. Due to the resiliency, technology refresh, industrial base, and adaptability advantages already mentioned, the US is likely to eventually transition to disaggregated architectures; the timing and risk associated with that transition, however, are important unknown details. The cost ramifications of disaggregation will drive the timing and risks, so understanding those cost ramifications, with the underlying cost drivers and trends, is of crucial importance and the subject of this research. Cost advantages will emerge from disaggregated architectures when the US significantly reduces launch costs, significantly increases resiliency requirements, and/or values architecture flexibility more highly. Since all three of these trends favorable to disaggregated architectures are already occurring, those conducting analyses of architecture alternatives should explicitly model excursions to address these trends. Only by doing so will they capture the cost benefits of disaggregation.

To illustrate the principles and complexity of analyzing the cost ramifications of disaggregation, this research uses a hypothetical communications space architecture example. Adopting a hypothetical architecture avoids classification and proprietary issues without sacrificing general principles or conceptual understanding. While the architecture is hypothetical, the cost estimates are realistic and based on published models and information. The paper presents a baseline cost analysis of a disaggregated vs. an aggregated architecture. From that baseline, excursions show the impact of changes to launch costs, resiliency requirements, and architecture flexibility requirements. The paper then presents some important disaggregation implementation considerations and concludes with recommendations.

Life Cycle Cost Estimating for Space Systems—Baseline Case

The practice of formal cost estimating in defense acquisition dates back to 1936, when T.P. Wright developed "learning curve" equations to predict aircraft manufacturing costs over long production runs.[7] Techniques evolved through World War II and models became more sophisticated. In 1986 Congress amended Title 10 to mandate independent life-cycle cost estimates for major defense acquisition programs.[8] Cost modeling cannot prevent acquisition program cost overruns, but accurate cost estimates are an important planning and decision tool within the DoD acquisition process.

Unmanned Space Vehicle Cost Model

Today, cost experts at SMC, Air Force Cost Analysis Agency, Office of the Secretary of Defense Cost Assessment and Program Evaluation, and National Reconnaissance Office (NRO) Cost Group use a model called the Unmanned Space Vehicle Cost Model (USCM) for space system cost estimating.[9] USCM is a parametric estimating tool based on cost estimating relationships built from a factual historical database. The Cost Analysis Division of the Space

and Missile Systems Organization published the first version of USCM in 1969 and has updated the model repeatedly over the past 40+ years. Version 9 is the version currently in use and contains cost data from 87 military, National Aeronautics and Space Administration (NASA), and commercial satellites.[10]

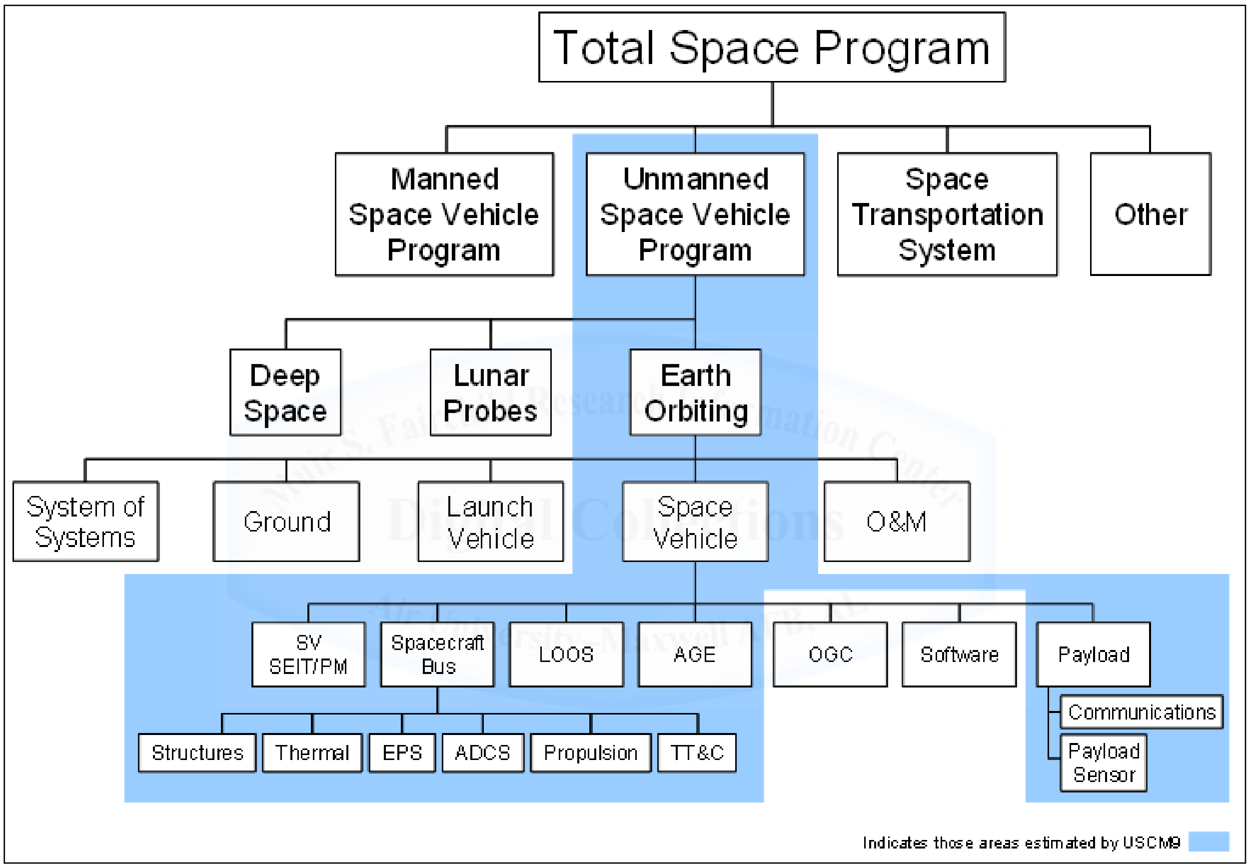

Figure 1. Unmanned Space Vehicle Cost Model (reprinted from Space and Missile Systems Center, *USCM Online*)

Figure 1 depicts the scope of the USCM model. When generating cost models and cost estimates, it is extremely important to understand what costs are included and excluded. Of particular note for USCM, the model only generates cost estimates for the space vehicle. To generate a full life-cycle cost estimate, other costs related to the mission must be included, the most significant of which are typically launch, ground system, and operations. Launch costs can

be estimated relatively accurately from historical actuals once the launch vehicle is known. Ground system and operations costs vary widely across mission areas depending on operational concepts, but the number of satellites in the architecture is typically only a second-order cost driver. The cost to operate the Global Positioning System constellation, for example, does not depend significantly upon whether there are 24 or 30 satellites on orbit because the same people and ground equipment are required for either constellation size. For purposes of this high-level study of disaggregation, it is reasonable to assume that any deltas between aggregated and disaggregated architectures in ground system and operations costs are insignificant relative to the deltas in space vehicle and launch costs. Similarly, program management, system engineering, and data fusion in a disaggregated architecture are likely to be different than in an aggregated system, with fewer integration challenges in space but more on the ground. These differences are important, but in most architectures will not rise to the level of becoming significant system-level cost differentiators. A recently-completed Joint Overhead Persistent Infrared (OPIR) Integrated Space Trade (JOIST) study provides additional data to support these simplifying assumptions.[11]

Communications Architecture Example

As a baseline case of disaggregation cost analysis, consider the 8,760-pound example communications satellite used to illustrate the USCM model.[12] For conceptual and mathematical simplicity, assume this communications satellite could be "perfectly" disaggregated into four satellites, each weighing one-fourth as much (2,190 pounds) and possessing one-fourth the capability of the large satellite. This assumption represents a hypothetical best-case disaggregation scenario; perfect disaggregation, in which weight scales exactly proportional to capability, is usually not possible because physics drives the weight of certain components, such

as feed horns and optics, and because a portion of a satellite's weight is dedicated to bus overhead functions that do not scale linearly with payload capability.[13]

In addition, assume no learning curve since the production numbers are small in both cases. Use a standard inflation factor of 1.133[14] to inflate the output of the USCM model, which is in 2006 dollars, to 2013 dollars. There are many variables involved in estimating launch costs, but for illustrative purposes assume the satellites will be launched by United Launch Alliance (ULA), the only current DoD launch provider for satellites of this size, for $464M per launch[15] and that two of the disaggregated satellites could be launched at once, a concept known as "dual launch."

The USCM calculation details for this communications architecture example are shown in appendix 1 and summarized in Table 1. The results show that even with the assumption of perfect disaggregation, the disaggregated architecture is significantly more expensive. The cost disadvantages of the disaggregated architecture are further exacerbated if the government has already paid the non-recurring engineering (NRE) for the aggregated system or if dual launch is not implemented.

Table 1. Baseline cost comparison for disaggregating a communications satellite

	Aggregated	**Disaggregated**
# satellites	1	4
Weight per satellite (lbs.)	8,760	2,190
Space vehicle NRE cost (FY13$M)	380	150
Space vehicle unit cost (FY13$M)	236	83
# launch vehicles	1	2
Launch vehicle unit cost (FY13$M)	464	464
Total cost (excluding ground and operations)	**$1.08B**	**$1.41B**

This example illustrates the fundamental challenge the US faces in pursuing disaggregation: it almost always appears that it will cost more. This finding is not particularly surprising because contractors and program offices performed extensive analysis to arrive at today's architectures. Fundamentally, architectures containing large spacecraft are cost-effective because multiple payloads can share common bus services and launch costs. This phenomenon is not limited to government missions. The companies that build commercial communications satellites would have disaggregated long ago if doing so would have increased profits.

Is disaggregation therefore doomed to failure, especially in a time of declining budget resources? Not necessarily. The Achilles' heel of cost analysis lies in the underlying assumptions. In addition to questioning their assumptions, program offices and cost estimators should perform sensitivity analysis to determine the key cost drivers. Some of them are not as rigid as is often assumed.

Sensitivity Analysis, Changing Assumptions, and Key Cost Drivers

Cost analysts base nominal cost analyses such as the comparison in the previous section on many underlying assumptions. They must use assumptions to reduce the trade space to a manageable size, but it is vital to question those assumptions carefully because they can change over time. In addition, sometimes explicit actions can be taken to change assumptions that are significant cost drivers. Three particularly important assumptions for the communications satellite example are launch costs, resiliency requirements, and architecture flexibility requirements.

Launch Costs

An examination of Table 1 reveals that launch costs are the largest line item and therefore a key cost driver. ULA's launch costs for the Evolved Expendable Launch Vehicle recently rose to $69.6B for 150 launches through 2030, an average cost of $464M per launch, more than double the previous cost of $230M per launch.[16] To pursue alternatives, the Pentagon took a significant first step toward ending the ULA monopoly in December 2012 when the Undersecretary of Defense for Acquisition, Technology, and Logistics authorized the Air Force to purchase up to 14 of the 50 rockets needed during the next five years on a competitive basis.[17] Just a week prior to that announcement, the Air Force awarded contracts to Lockheed Martin, Orbital Sciences, and SpaceX to provide small-satellite launch services.[18] SpaceX has an existing contract with NASA to resupply the International Space Station for under $133M per launch, and Orbital has a similar contract for under $238M per launch.[19] SpaceX advertises its Falcon 9 rockets for $54M per launch,[20] almost one-tenth the latest EELV cost estimate. For small satellites the competitive situation is even more advantageous; the Air Force has been launching small satellites using residual Minuteman II and Peacekeeper motors since 1996 at a cost of $20-30M per launch; 1300 Minuteman II motors and dozens of Peacekeeper motors remain in storage and could be used for this purpose.[21]

Finally, highly reliable foreign launches are available from Europe or Russia for $20-220M.[22,23] In general, the US National Security Strategy and National Security Space Strategy emphasize partnering with allies.[24,25] With regard to foreign launch services, however, the US Space Transportation Policy states, "United States Government payloads shall be launched on space launch vehicles manufactured in the United States, unless exempted by the Director of the Office of Science and Technology Policy, in consultation with the Assistant to the President for

National Security Affairs."[26] The intent is clearly to favor US launch capabilities, but the policy does not completely close the door on the use of foreign launch capabilities. In addition to this policy barrier, security requirements may preclude the foreign launch of some satellites. Nevertheless, the US fiscal crisis and the potential to save perhaps 75% of the $70B slated for ULA launches may open some doors for the use of foreign launch in selected cases and/or as a backup to US commercial capabilities, so that sole-source ULA contracts can be completely terminated.

The bottom line with respect to launch costs is that the DoD could significantly reduce them by competitively procuring launches. Table 2 shows the positive impact this change would have on disaggregation costs. Switching to SpaceX launches drives down the cost of both the aggregated and disaggregated architectures, as expected. For each architecture, the impact of lowering launch costs is proportional to the number of launch vehicles required. Since the disaggregated architecture requires two launch vehicles, as compared to the one required for the aggregated architecture, switching to SpaceX drives the cost of the disaggregated architecture down twice as much as it drives down the cost of the aggregated architecture. The result is that the disaggregated architecture becomes the least expensive. Disaggregating and lowering the cost of launch go hand-in-hand; disaggregating without breaking the bank requires lower launch costs, and lower launch costs cause disaggregation to become fiscally attractive in some circumstances.

Table 2. Disaggregation cost comparison with competitive launch costs

	Aggregated (Baseline)	Aggregated w/ SpaceX	Disaggregated w/ SpaceX
# satellites	1	1	4
Weight per satellite (lbs.)	8,760	8,760	2190
Space vehicle NRE cost (FY13$M)	380	380	150
Space vehicle unit cost (FY13$M)	236	236	83
# launch vehicles	1	1	2
Launch vehicle unit cost (FY13$M)	464	54	54
Total cost (excluding ground and operations)	**$1.08B**	**$0.67B**	**$0.59B**

Resiliency

The second important assumption and cost driver is resiliency requirements. Launch vehicles can explode, satellites can collide with other satellites or space debris, and anti-satellite weapons or high-altitude nuclear detonations can destroy critically-needed satellites,[27] so resilience against at least some of these threats is important. Senior leaders recognize the emerging importance of resilience,[28] but have not yet incorporated it into space architectures to the extent that air, sea, land, or even cyber environments have. One reasonable change to address resiliency would be to require that each space architecture continue to meet user requirements after loss of one satellite.

Viewing resiliency in this simplified manner enables it to be easily incorporated into cost estimates. Continuing with the example of disaggregating a communications satellite, Table 3 shows that when the resiliency requirement is added, the disaggregated architecture becomes even more cost advantageous. As compared to the baseline, both resilient architectures are less expensive, which illustrates that the opportunity cost of remaining with ULA as the monopoly launch provider can be viewed as either lost resiliency or, if the value of resiliency is ignored, foregone doubling of communication capability from building and launching a second satellite.

Table 3. Disaggregation cost comparison with resiliency requirement added

	Aggregated (Baseline)	Aggregated Resilient w/ SpaceX	Disaggregated Resilient w/ SpaceX
# satellites	1	2	5
Weight per satellite (lbs.)	8,760	8,760	2,190
Space vehicle NRE cost (FY13$M)	380	380	150
Space vehicle unit cost (FY13$M)	236	236	83
# launch vehicles	1	2	3
Launch vehicle unit cost (FY13$M)	464	54	54
Total cost (excluding ground and operations)	**$1.08B**	**$0.96B**	**$0.73B**

Flexibility

A third cost driver is flexibility. Relatively frequent requirement changes, while always unwelcome to a program, are a fact of life because today's threats and opportunities evolve rapidly; the stability of the Cold War is over, but the DoD still unrealistically expects space programs to solidify requirements a decade or more in advance because of long build times for large, aggregated satellites. One simple but reasonable approach to capturing the value of flexibility is to assume that a re-design, build, and launch of a modified satellite will be required at some point after the initial design is completed. Additional NRE, an additional satellite vehicle, and an additional launch vehicle must therefore be added to each architecture.

Table 4 displays the cost ramifications of incorporating this flexibility requirement. The bottom line is that the disaggregated, resilient, and flexible architecture is 38% less expensive than the aggregated, resilient, and flexible architecture. Importantly, the disaggregated, resilient, and flexible architecture is also still less expensive than the baseline architecture and provides 25% more communication capability to the warfighter.

Table 4. Disaggregation cost comparison with flexibility requirement added

	Aggregated (Baseline)	Aggregated Resilient Flexible w/ SpaceX	Disaggregated Resilient Flexible w/ SpaceX
# satellites	1	3	6
Weight per satellite (lbs.)	8,760	8,760	2,190
Space vehicle NRE cost (FY13$M)	380	760	300
Space vehicle unit cost (FY13$M)	236	236	83
# launch vehicles	1	3	4
Launch vehicle unit cost (FY13$M)	464	54	54
Total cost (excluding ground and operations)	**$1.08B**	**$1.63B**	**$1.01B**

Consequences of Revisiting Assumptions

Assumptions made with respect to launch costs, resiliency requirements, and flexibility requirements are important drivers of the cost ramifications of disaggregation. Rather than continuing to assume these three factors are unchanging or unchangeable, the US space enterprise should explicitly include excursions to the nominal assumptions for these factors when evaluating disaggregation options.

These excursions are especially critical because the trend in each of these factors favors disaggregation. Launch costs will come down because remaining with ULA as a monopoly provider is unsustainable in the current and foreseeable budget environment. Fortunately, other launch options are readily available in the US commercial sector and, if needed, European and Russian providers also offer very reliable and low cost launch capabilities. Resilience is increasing in importance as space becomes increasingly congested, contested, and competitive[29] and, absent any disaggregation, the fragility of the US constellations will increase due to declining numbers of satellites and DoD programs.[30] Flexibility is also increasing in importance due to the rapid rate of technological and threat changes, as evidenced by recent urgent “gap-

filling" programs needed because of acquisition failures.[31] Satellites that continue to require 10-14 years to design may be obsolete before launched.

Due to these trends, the US should proceed with disaggregating architectures more aggressively, as soon as cost ramifications are understood and acceptable with the assumption excursions outlined herein. A cautious approach to disaggregation is ideal from the perspective of minimizing technical risk. Retain legacy capabilities until new capabilities are proven[32] and proceed at the pace of available funding. Unfortunately, in today's resource constrained environment, cautious disaggregation will continue to appear to be another good idea that is unaffordable. Without infusing additional funding or accepting some additional architecture risk, little disaggregation will occur. The consequences of that failure will be broken architectures, more emergency "gap filling," and dramatically reduced space capabilities. Given the US dependence on space capabilities,[33] these capability gaps are simply not acceptable when viable disaggregation alternatives exist. In other words, pursuing disaggregation more aggressively may involve some risk to individual architectures, but the risk of not doing so may be even greater.

Pursuing disaggregation aggressively does not mean pursuing it blindly. There are natural limits to disaggregation. First, some missions cannot be disaggregated because of technical requirements; in an imagery satellite, for example, a particular lens size may be required, it may be large, and there may already be no other payloads on the satellite. However, it is essential to view disaggregation as splitting out missions rather than merely space hardware. Applying this perspective to the imagery example, it may be possible to disaggregate medium-resolution imagery from high-resolution imagery as two distinct missions that could be performed from two varieties/sizes of satellite instead of one. The strongest cases for

disaggregation will be multi-mission satellites with severable hardware combined onto a single bus, especially when the bus requirements for one mission differ or conflict with the bus requirements for the other mission. For example, Space-Based Infrared System (SBIRS) satellites have two payloads, one that moves while the other must remain stationary, and Advanced Extremely High Frequency (AEHF) satellites have two payloads, one that requires nuclear hardening while the other does not.

Finally, note that hosted payloads, such as the recent flight of the Commercially Hosted Infrared Payload (CHIRP) experimental missile-warning sensor on an SES Americom communications satellite,[34] are an example of architecture disaggregation, but not satellite disaggregation. From the payload and satellite perspective, hosted payloads represent aggregation, the combining of two missions onto one large satellite; the hosted payload concept shifts the integration challenges and other problems associated with aggregation to another entity.[35] The apparent cost advantages of hosted payloads often accrue from using foreign or commercial launch services. To ensure best value for the government and compare concepts on an apples-to-apples basis, program managers considering hosted payloads must also consider dedicated, government-owned small satellites launched on foreign or commercial rockets. Hosted payloads are therefore an example of partial disaggregation. They represent a step in the right direction, but payloads should be shifted to mission-specific smaller satellites to fully achieve the desired enterprise-level benefits of disaggregation.

Implementation Considerations

Once the US space enterprise decides or accepts that some disaggregation will occur in some of the US space architectures within the near future, then the key set of questions shifts from "whether" and "when" to "how," and especially how to manage budgets and risk during the transition to disaggregated architectures. This section focuses on this next layer of implementation details and, in particular, on budget phasing issues, formal requirement changes, and countering inertia and self-interest of contractors and program offices.

Budget Phasing

One of the advantages of disaggregated architectures is that small satellites can be built faster than the typical 10-year lead time for a large satellite. Given that satellites have finite lifetimes and that the US wishes to maintain a constant capability on orbit, navigating the transition from aggregated to disaggregated architectures requires careful budget phasing because of these different and changing lead times. As a simple example, consider an architecture that requires five satellites on orbit. If each satellite lasts five years, one satellite must be launched each year, on average, to maintain the on-orbit capability. With a 10-year lead time, the satellite that needs to be launched in 2023 must be started in 2013. If, however, a satellite in this architecture could be replaced by four smaller satellites with a 5-year lead time, then the four smaller satellites to be launched in 2023 do not need to be started until 2018. Figure 2 displays year-by-year details for the communications satellite example. Viewing the architecture from a budget phasing perspective reveals a "disaggregation dividend" harvestable from near-term budgets without any degradation in on-orbit capability.

	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
COA 0: Baseline -- Build 1 Large Sat/Yr																	
Starting Capability On Orbit	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
# Large Sats Launched	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
# Large Sats De-Orbited	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
Ending Capability on Orbit	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Production Funding Required	$236	$236	$236	$236	$236	$236	$236	$236	$236	$236	$236	$236	$236	$236	$236	$236	$236
COA 1: Transition from 1 Large Sat/Yr to 4 Small Sats/Yr																	
Starting Equiv Capability On Orbit	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
# Large Sats Launched	1	1	1	1	1	1	1	1	1	1	1						
# Small Sats Launched (0.25 capability each)												4	4	4	4	4	4
# Large Sats De-Orbited	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	
# Small Sats De-Orbited (0.25 capability each)																	-4
Ending Equiv Capability On Orbit	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
R&D Funding Required (NRE + first 2 sats)							$466										
Production Funding Required	$236	"Disaggregation Dividend"					$166	$332	$332	$332	$332	$332	$332	$332	$332	$332	$332

Circles signify:
1. Lead time for large satellites = 10 years
2. Lead time for small satellites = 5 years
3. "Disaggregation Dividend" = no funding required 2013-2017

Assumptions:
User requirement: equivalent of 5 large sats on orbit
Large Sat: 10 year lead time, 5 year life
Small Sat: 5 year lead time, 5 year life

Figure 2. Space vehicle budget profiles for migration to disaggregated architecture

An additional near-term disaggregation dividend can arise from the different "colors" of money the Space and Missile Systems Center (SMC) uses for development and production. SMC builds the first two satellites of a series with development (3600) funds and any additional satellites in the series with procurement (3020) funds. A "full funding" requirement that an end item be fully budgeted in the year the contract is awarded applies only to 3020 funding. When an architecture is disaggregated, these rules permit an additional disaggregation dividend to be harvested from near-term budgets because the funding for the first two new satellites can be spread across several years instead of concentrated in the first year.

These near-term disaggregation dividends can also be understood in the context of lean production principles; work-in-progress is a form of waste, and migrating from long-lead satellites to short-lead satellites generates immediate cost savings by reducing work-in-progress.[36] Even though production quantities of space systems are typically low, their extremely high cost amplifies the potential payoff of applying lean production principles.

Formal Requirement Changes

A second important implementation consideration revolves around the issue of how and when to document revised requirements for low-cost launch, resilience, and architecture flexibility for the programs within each architecture area. The process for documenting requirements for space systems, as for all major DoD acquisition programs, is to use the Joint Capabilities Integration and Development System (JCIDS) or Intelligence Community Capability Requirements Process,[37] as appropriate. Both processes typically require millions of dollars of supporting analysis and document preparation and several years of effort. Figure 3 illustrates the JCIDS process. The reason for raising this topic as an implementation consideration is to note that each program contemplating disaggregation should review its guiding requirements documents to determine any needed revisions. In addition and while awaiting these JCIDS updates, AFSPC and the NRO should consider publishing policy guidance urging or requiring programs to consider and place value in low-cost launch, resilience, and flexibility. For example, a policy could state that all programs shall disaggregate their architectures/satellites, competitively procure launch services, meet specified resilience and flexibility constraints, and obtain 3-star-level waivers for policy noncompliance. Such a policy would urge programs toward disaggregation while still allowing reasonable waivers.

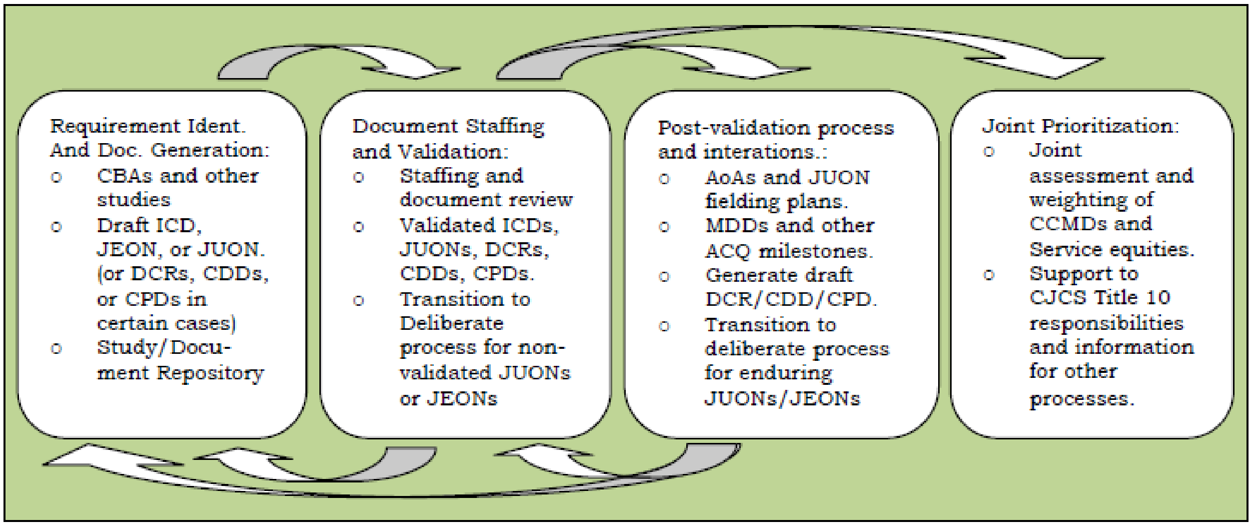

Figure 3. Joint Capabilities Integration and Development System Process (reprinted from Joint Chiefs of Staff, *CJCSI 3170.01H*, A-1)

Countering Inertia and Self-interest

Finally, a third implementation consideration is for leaders to recognize that the migration toward disaggregated architectures is going to be difficult, politically more than technically. The DoD acquisition system inadvertently favors large, expensive, multi-mission platforms such as the current aggregated space architectures. Three particularly pertinent reasons for this phenomenon are:

1. Contractor profit motives favor complexity and aggregation. More contractors possess the skills and expertise to construct small satellites than to construct large and complex satellites, so disaggregation is likely to increase competition and lower profit margins. Adding a payload to an existing satellite, on the other hand, boosts the incumbent contractor's profits without any competition.
2. Cost overruns result in few if any negative consequences. The DoD budget process usually prioritizes "disconnect" overruns above "initiatives"[38] and the DoD rarely cancels programs that overrun, even after repeated Nunn-McCurdy breaches.

Bureaucracies and contractors strive to increase their budgets and there are very few "new starts," so cost overruns are sometimes the easiest way to increase budget, power, and profits. This motivation is especially strong when combined with cost plus contracts and/or program offices that readily award scope-increasing contract modifications. These cost overruns are more common on complex systems.

3. The budget process encourages aggregation. Contractors and program offices can successfully deflect the inevitable 10-20% budget cut by explaining, if true, that cutting even $1 would require cancellation of a very large unit of warfighter capability. Program offices with a few aggregated satellites therefore possess more power within the bureaucracy to deflect budget cuts than program offices with a larger number of disaggregated satellites, all other factors being equal. Firm fixed price and multi-year contracts, when a contractor and program office can arrange them, convey similar power to deflect cuts.

Countering these powerful incentives and the other inertia of the status quo to oppose disaggregation will be difficult. Once leaders recognize the challenges, though, they can counter the bureaucracy's and contractors' undesirable natural tendencies by strengthening independent government system engineering and cost estimating capabilities, conducting more frequent competitions, and shifting some integration responsibilities away from the prime contractor. Excellent people behaving with integrity populate the national security space enterprise. If senior leaders are not obtaining the affordable and resilient disaggregation they desire, they must 1) recognize the incentives they have put in place, and 2) use policy and the checks and balances within their organizations to counter and shift those incentives.

Acquisition became relatively easy when the money spigot turned on in 2001; that era has ended. Leading the space enterprise through disaggregation and the other changes needed to thrive in a period of declining resources will be a challenging endeavor. To pursue disaggregation successfully, leaders within the national security space enterprise must carefully consider implementation details relating to budget phasing, formal requirement changes, and countering inertia and self-interest.

Conclusions and Recommendations

The US should pursue space disaggregation more aggressively. In addition to the well-recognized advantages of resiliency, technology refresh, industrial base, and adaptability, many disaggregated architectures could be less expensive than the baseline architectures. Cost advantages will emerge from disaggregated architectures when the US significantly reduces launch costs, significantly increases resiliency requirements, and/or values architecture flexibility more highly. All three of these trends favorable to disaggregated architectures are occurring and the US could accelerate them to enable cost-effective disaggregation.

In order to reap the financial benefits of disaggregation, **the US should end the ULA monopoly on launch.** The monopoly is inconsistent with free-market values and the opportunity cost of continuing it may now exceed 75% of $70B through 2030. The US desperately needs those funds for building the satellites themselves. Switching to competitively procured US commercial launch capabilities, backed up by foreign capabilities when needed, will dramatically lower the cost of launch and thereby enable disaggregation to be financially viable.

A policy change that would accelerate ending the ULA monopoly would be to include launch costs in the budget for the satellite being launched, rather than as a separate line item, and

empower each satellite program manager to choose the launch option that is best for his or her system. Doing so would empower program managers to optimally manage risk across their entire system and incentivize them to elect less expensive launch options, when appropriate for their system, by allowing them to use the resultant savings to improve satellite capabilities. When launch becomes a commercial commodity it will no longer make fiscal sense to centrally manage it at the MAJCOM or Center level. Unfortunately, centrally managing launch at the MAJCOM and Center levels may slow the commoditization process.

In addition to lowering launch costs, **the US national security space enterprise should incorporate resiliency requirements into space architectures.** One simple approach would require each architecture to survive the loss of one satellite. There are many other approaches. The important point is that program offices respond to requirements, and if resiliency is not a requirement then space architectures are not going to be resilient. Incorporating resiliency into requirements will make disaggregated architectures more financially appealing; it is also the right thing to do for space protection.

The pace at which technology and threats are evolving requires flexibility in US space architectures, so **the US national security space enterprise should value architecture flexibility more highly.** Rather than locking the nation into decades of building only a few large and expensive satellites, program offices should assume that some requirements will evolve. Doing so will highlight one of the key benefits of disaggregation.

Finally, the US must recognize that the transition to disaggregated architectures will be challenging, politically more than technically. **US space leaders should pay attention to implementation details such as budget phasing, formal requirements and policies, and countering inertia and other barriers to change.**

The US space enterprise is evolving. Changes are inevitable, driven by sweeping and powerful global trends. Since the only alternative is irrelevance, the US space enterprise must embrace these changes and turn them into opportunities. Disaggregating will be challenging, but by viewing it as an opportunity rather than a threat, the US will emerge stronger and more capable. By implementing smooth, deliberate, and thoughtful disaggregation, the US will continue to lead the world in space technology, acumen, and capability.

Appendix 1

This appendix contains the details of the Unmanned Space Vehicle Cost Model (USCM) inputs and outputs for the communications disaggregation example used in Table 1 through Table 4. Figure 4 shows the exact inputs used and Figure 5 the exact cost estimates generated by the model.

WBS	Cost Drivers	Input (Aggregated)	Input (Disaggregated)	Units
Structure & Thermal				
Nonrecurring	Structure Subsystem Weight + Thermal Subsystem Weight	5,656	1,414	lbs
	Structure/Thermal NR Class (1 = new development, 0 = modified design)	1	1	
Recurring	Structure Subsystem Weight + Thermal Subsystem Weight	5,656	1,414	lbs
Electrical Power Subsystem				
Nonrecurring	EPS Subsystem Weight	1,223	306	lbs
	EPS NR Class (1 = new development, 0 = modified design)	1	1	
Recurring	EPS Subsystem Weight	1,223	306	lbs
	Agency (1 = Government, 0 = Commercial)	1	1	
Attitude Control Subsystem				
Nonrecurring	ACS Subsystem Weight	615	154	lbs
	ACS NR Class (1 = new development, 0 = modified design)	1	1	
Recurring	ACS Subsystem Weight	615	154	lbs
	Agency (1 = Government, 0 = Commercial)	1	1	
Propulsion Subsystem				
Nonrecurring	Average Propulsion NR Cost	4,250	4,250	FY06$ (K)
Recurring	Propulsion Subsystem Weight	528	132	lbs
	Agency (1 = Government, 0 = Commercial)	1	1	
Telemetry, Tracking, and Command Subsystem				
Nonrecurring	TT&C Subsystem Weight	240	60	lbs
	Has Transponder (1 = Yes, 0 = No)	1	1	
Recurring	TT&C Subsystem Weight	240	60	lbs
	Agency (1 = Government, 0 = Commercial)	1	1	
Communication #1				
Nonrecurring	Communication Payload Hardware Subsystem Weight	498	125	lbs
Recurring	Communication Payload Hardware Subsystem Weight	498	125	lbs
	Government Program w / Comm Payload operating at EHF or higher (1 = Yes, 0 = No)	1	1	
Space Vehicle Total Weight		8,760	2,190	lbs

Figure 4. USCM inputs for communications satellite disaggregation example

	Aggregated FY06$ (K)		Disaggregated FY06$ (K)	
WBS	**NRE**	**T1**	**NRE**	**T1**
Space Vehicle	$ 335,338	$ 207,858	$ 132,168	$ 73,585
SEPM	$ 61,100	$ 34,787	$ 24,082	$ 12,315
Integration and Test	$ 23,338	$ 13,590	$ 10,633	$ 6,804
Spacecraft Bus	$ 143,611	$ 98,172	$ 60,250	$ 30,680
Structure & Thermal	$ 48,062	$ 32,815	$ 21,095	$ 9,555
Electrical Pow er Subsystem	$ 17,790	$ 17,406	$ 5,844	$ 5,774
Attitude Control Subsystem	$ 46,052	$ 22,596	$ 18,625	$ 7,642
Propulsion Subsystem	$ 4,155	$ 10,487	$ 4,155	$ 3,527
Telemetry, Tracking, and Command	$ 27,552	$ 14,870	$ 10,530	$ 4,182
Communication #1	$ 107,289	$ 61,308	$ 37,203	$ 23,785
LOOS		$ 23,521		$ 5,880
AGE	$ 9,492		$ 8,298	

Inflation Factor (FY06 to FY13): 1.133	Aggregated FY13$ (K)		Disaggregated FY13$ (K)	
WBS	**NRE**	**T1**	**NRE**	**T1**
Space Vehicle	$ 379,938	$ 235,503	$ 149,747	$ 83,371

Figure 5. USCM outputs for communications satellite disaggregation example

Notes

(All notes appear in shortened form. For full details, see the appropriate entry in the bibliography.)

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